ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY

COLLEGE OF ARCHITECTURAL AND CIVIL ENGINEERING

REPAIR AND STRENGTHENING OF REINFORCED CONCRETE BEAMS USING NEAR-SURFACE MOUNTED FIBER REINFORCED POLYMER RODS

A thesis submitted to the College of Civil and Construction Management Technology, School of Graduate Studies, Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science in Structural Engineering.

By

Mehret Redae

Jan, 2017

Addis Ababa, Ethiopia

ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY

COLLEGE OF ARCHITECTURAL AND CIVIL ENGINEERING

Repair and Strengthening of Reinforced Concrete Beams using Near-Surface Mounted Fiber Reinforced Polymer Rods

by

Mehret Redae

(January, 2017)

Acknowledgement

All of the success I have acquired on the journey of doing this thesis is through the will of the Almighty God which I'm most thankful.

My outmost gratitude goes to my advisor, Dr. Abraham Gebre, for his devotion, consistent consultation, encouragement and unreserved support.

I am also thankful for the staff members at Addis Ababa Science and Technology University (AASTU) and at Addis Ababa institute of Technology (AAiT) for their unlimited support and cooperation.

Finally, I am grateful to my family and friends for their full support, encouragement throughout this journey.

Table of Contents

List of Tables

List of Figures

List of Acronyms

NSM : Near surface mounted

FRP: Fiber reinforced polymer

GFRP: Glass Fiber reinforced polymer

LVDT : Linear variable differential transducers device

MPa : Mega Pascal

Abstract

The majority of the buildings and other infrastructures in Ethiopia are mainly constructed of reinforced concrete (RC) structures. Through time, these structures tend to deteriorate due to the estimated durability time, poor technique at the early stage of construction or over loadings. For durable and effective usage of these structures to function as designed, repairing and strengthening becomes a necessity. Near surface mounted (NSM) Fiber reinforced polymer (FRP) is a new and promising technique for increasing the flexural and shear strength of RC members. This study is aimed to investigate the effectiveness and enhancement in capacity of the flexural strengthened RC beam structures using Near surface mounted (NSM) Glass Fiber reinforced polymer (GFRP) rods as compared to non-strengthened/control beam. The experimental study was conducted by loading the beams under center-point bending and instrumented with linear variable differential transducers device, LVDT and strain gauges to monitor deflection and strains at the mid-span location on the concrete beam and FRP respectively. Performance of the tested beams and their modes of failure is presented in this paper. The test results confirmed that the flexural performance of NSM GFRP strengthened beams increased on average of 21 to 30 % over the non-strengthened beams proposing this technique can be used for repairing and rehabilitation purpose of RC members.

Key words: Retrofit, Near surface mounted, Fiber reinforced polymer, Glass, Flexural, LVDT, strain gauges, RC beam.

Chapter 1

1. Introduction and Background

1.1 Introduction

Repairing and strengthening mechanism (the collective term retrofit, which implies the addition of structural components after initial construction, captures both rehabilitation and strengthening) for damaged reinforced concrete structures is done frequently. Most of the damage is due to poor construction, repeated loading or sudden impacts on the structural members, which is a cause for the failure of the structures before their predicted age. The usual method of repairing or rehabilitation of concrete structures is concrete jacketing or any other external strengthening methods. Nowadays, the use of Near Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) rods is becoming an attractive method for increasing flexural strength of deficient reinforced concrete (RC) members. This is mainly because the NSM system has a number of advantages: (a) the amount of site installation work may be reduced, as surface preparation other than grooving is no longer required (e.g., plaster removal is not necessary; irregularities of the concrete surface can be more easily accommodated; removal of the weak laitance layer on the concrete surface is no longer needed); (b) NSM reinforcement is less prone to debonding from the concrete substrate; (c) NSM bars can be more easily anchored into adjacent members to prevent debonding failures; this feature is particularly attractive in the flexural strengthening of beams and columns in rigidly-jointed frames, where the maximum moments typically occur at the ends of the member; (d) NSM reinforcement can be more easily pre-stressed; (e) NSM bars are protected by the concrete cover and so are less exposed to accidental impact and mechanical damage, fire and vandalism; this aspect makes this technology particularly suitable for the strengthening of negative moment regions of beams/slabs; (f) the aesthetic of the strengthened structure is virtually unchanged. The above advantages make the NSM FRP method preferable in many cases to the externally bonded strengthening methods (De Lorenzis and Teng, 2006). In this study, experimental investigations on NSM GFRP strengthened RC beams were carried out. Based on the study, 14.25-25.58 % increase for the first trial tests and 24.89-35.68% increase for the second trial tests were obtained.

For this experimental study, assumptions were made in the reinforced concrete:

A) Plane cross-section remain plane;
B) Small deformations;
C) No slip between any longitudinal reinforcement and concrete;
D) No tensile strength of concrete after cracking;
E) Stress-stain relationships of materials as determined by standard uniaxial tests are representative of their behavior as part of the beam (EBCS part 2, 1995).

1.2 Objective of the study

1.2.1 General objectives

The study is to carry out a preliminary investigation on FRP rods for replacing the deficient and damaged bottom (tensile) side of RC beam members. The main objective of this study is to investigate the load carrying capacity and also the enhancement of the deformability that is to be obtained in FRP strengthened RC beam member as compared to the non-strengthened RC beam.

1.2.2 Specific objectives

In brief detail, the objectives of the investigation are as follows:

- To experimentally investigate the flexural behavior of RC beams strengthened with Glass FRP rods. The experimental program was carried out to study the effect of FRP rod material, number and area of bars, bond length, epoxy properties, and strengthening arrangement on the flexural response of RC beams strengthened with NSM FRP reinforcement.
- Investigate and compare the failure mechanisms of NSM FRP strengthened RC beam members as compared to the non-strengthened RC beam.

The significance of this experiment is to provide a new and effective method of repairing and rehabilitation for damaged buildings. Also most of the bridge structures in our country require rehabilitations due to the reaching of the designed age or over loading on the bridge structures. According to the new Ethiopian building code, the capacity of the bridges needs to be upgraded and this experiment provides a new and promising retrofitting material for the method of rehabilitations.

1.3 Statement of the problem

This experimental study was done to provide solutions for repairing and rehabilitation for the current problems in the construction industry. These common problems include:

- Deteriorating and damaged RC beams and columns in buildings,
- Old and damaged bridges in need of repairing and strengthening due to design age or overloading on the bridges which are expected to transport heavy equipment.

1.4 Thesis layout

This thesis consists of consists of the following chapters.

Chapter 1 gives a brief introduction to the need for repairing and strengthening of RC beams. The NSM technique and its advantage are also briefly discussed. The objectives of the proposed research work are identified in this chapter.

Chapter 2 reviews detailed literatures on the definition of composite material and the different types of composite materials available. It continues to discuss the Glass fiber polymer rods and its properties and advantages relative to the other types of fiber polymers. This chapter also describes about the NSM technique and its emerging usage in the civil engineering sector. Previously done field works on prediction of behavior of RC beams strengthened with NSM FRP rods have been discussed in this chapter.

Chapter 3 discusses the details of experimental studies conducted on the beams which were tested under center-point loading arrangement.

Chapter 4 gives the experimental results and discussions for all beams with the different arrangement of GFRP rod. This chapter describes the failure modes and the load carrying capacity of the NSM FRP rod retrofitted beams relative to the control beam.

Finally, the conclusion for the experiment program is stated.

1.5 Scope and Limitations

In the experimental study, the beam sections were designed to fail in flexure by controlling the shear failure. This was done to compare the flexural capacity of the NSM GFRP beams with the control beams. The strain gauge readings were limited to some of the beams due to shortage of the gauges and so only the stated values on the diagrams have recorded values.

Chapter 2

2. Literature Review

2.1 Brief Review

Traditional methods of repairing of concrete structures with concrete and steel jacketing or any other external strengthening methods using steel materials have been used for some time. These methods often only restore a portion of the ultimate capacity of the damaged member and are left vulnerable to corrosion (Di Ludovico et al., 2010).These methods also are time consuming and labor intensive. They also increase the cross-sectional area of the structural members (Ibrahim and Mahmood, 2009). A concrete structure may have to carry large loads at a later date, or fulfill new standards. In extreme cases, a structure will have to be repaired due to sudden accidents. If any of these situations should arise it needs to be determined whether it is more economical to strengthen the existing structure or to replace it. In comparison to building a new structure, strengthening an existing one is often more complicated, since the conditions are already set (Nordin, 2003). A more recent method of repairing is the use of fiber reinforced polymers (FRP) because of their excellent mechanical properties, corrosion resistance, durability, light weight, ease of application, reduced construction time, efficiency, and low life cycle cost (Ibrahim and Mahmood, 2009). This literature review is limited to research on FRP composite materials inserted near the tensile surface of concrete beams. In particular, research studying the effect of NSM application of FRP materials on the flexural performance of reinforced concrete beams is reported.

The introduction of a composite material, Fiber Reinforced Polymer (FRP), to the civil engineering field has given the engineers a strengthening material that does not corrode, that is strong, stiff and lightweight.

2.2 The introduction of composites

Fiber Reinforced Plastic (FRP) products were first used to reinforce concrete structures in the mid-1950s. Today, these FRP products take the form of bars, cables, 2-D and 3-D grids, sheet materials, plates, etc. FRP products may achieve the same or better reinforcement objective of commonly used metallic products such as steel reinforcing bars, prestressing tendons, and bonded plates (ACI 440, 2007).

In the 1960s, corrosion problems began to surface with steel reinforced concrete in highway bridges and structures. Road salts in colder climates or marine salt in coastal areas accelerated corrosion of the reinforcing steel. Corrosion products would expand and cause the concrete to fracture. The first solution was a galvanized coating applied to the reinforcing bars. This solution soon lost favor for a variety of reasons, but mainly because of an electrolytic reaction between the steel and the zinc-based coating leading to a loss of corrosion protection (ACI 440, 2007).

The theory behind the construction of composite materials comes from the need to create a strong stiff and light material. Materials such as glass, carbon and Kevlar have extremely high tensile and compressive strength, but in solid form, many random surface flaws present in such materials, cause them to crack and fail at a much lower stress that it theoretically should. To overcome this problem, the material is produced in a fiber form, although the flaws will occur at the same frequency, the flaws will be reduced to a small number of fibers at any one point, and the remaining ones will carry the load with the materials theoretical strength. To prevent flaws occurring from abrasion on the surface of the material, or from existing flaws transferring to other fibers, it is necessary to isolate the fibers. This is why a resin matrix system is used. Mostly, composites are classified according to their matrix phase. The role of the matrix is to act as a medium to keep the fibers properly oriented and to protect them from the environment. The attractiveness of FRP composites as construction materials derives from a set of advantages comes from the tailorability of this material class through the synergistic combination of fibres in a polymeric resin matrix, wherein the fibre reinforcements carry load in predesigned directions and the resin acts as a medium to transfer stresses between adjoining fibres through adhesion and also provides protection for the fibres (Lukkassen and Meidell, 2007).

Composites have emerged as important materials because of their light-weight; high specific stiffness, high specific strength, excellent fatigue resistance and outstanding corrosion resistance compared to most common metallic alloys, such as steel and aluminum alloys. Other advantages of composites include the ability to fabricate directional mechanical properties, low thermal expansion properties and high dimensional stability. It is the combination of outstanding physical, thermal and mechanical properties that makes composites attractive to use in place of metals in many applications, particularly when weight-saving is critical. By carefully choosing the reinforcement, the matrix, and the manufacturing process that brings them together, engineers can tailor the properties to meet specific requirements (Lukkassen and Meidell, 2007).

2.2.1 Fiber-Reinforced Composites

Fiber Reinforced Plastics (FRP) is a general term for composite materials or parts that consist of a resin matrix that contains reinforcing fibers such as glass or fiber and have greater strength or stiffness than the resin. Fibers are the principal constituents in a fibre reinforced composite material. Fiber's properties depend strongly on both the external and internal fiber structure as well as the chemical composition therefore, their properties vary significantly. FRP is most often used to denote glass fiber-reinforced plastics (Lukkassen and Meidell, 2007).

A FRP reinforcement is a fiber reinforced polymer (FRP) (or fiber reinforced plastic) that is used as internal reinforcement, such as rebar, or externally bonded reinforcement used to strengthen concrete, masonry, steel, and timber structures.

FRPs uses for internal reinforcement and strengthening of structures use synthetic fiber in a polymeric matrix to provide excellent tensile strength in the direction of the fibers. The fibers are set in a straight, parallel and continuous arrangement within the matrix. These FRPs are sometimes known in the civil engineering community as high-strength composites. The first known use of FRPs as reinforcement occurred in 1975 in Russia. There, glass fiber reinforced polymer (GFRP) prestressing tendons were used to reinforce a 9m (30 ft.) long, glued timber bridge (Taerwe, 1995).

Significant studies of using FRPs as reinforcement began in Europe in the 1980's as an alternative to steel plate bonding for bridge repair and strengthening. FRP reinforcements gained significant support during the 1990's from research of magnetically levitated (maglev) train support structures in Japan. The Japanese in 1996 were the first to introduce design guidelines for FRP reinforced concrete (fib – federation internationale du béton, 2007).

Many terms have been used to define FRP composites. Modifiers have been used to identify a specific fiber such as Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), and Aramid Fiber Reinforced Polymer (AFRP). Another familiar term used is Fiber Reinforced Plastics. In addition, other acronyms were developed over the years and its use depended on geographical location or market use. For example, Fiber Reinforced Composites (FRC), Glass Reinforced Plastics (GRP) and Polymer Matrix Composites (PMC) can be found in many references. Although different, each of before mentioned terms mean the same thing; FRP composites (Tong et al., 2002).

Proper selection of the fibre is influenced by following characteristics:

- Density
- Tensile and Compressive strength
- Fracture
- Fatigue performance
- Response to impact loads
- Electrical and Thermal properties
- Cost

The predominant fibers used in FRPs related to structure reinforcement are:

i) Glass fiber

ii) Aramid fiber, also known as the trade names Kevlar and Technora

iii) Carbon fibre

iv) Basalt fiber

The common matrices used in FRP reinforcement products are:

- Epoxy
- Vinyl Ester

Both of these matrices are thermosetting resins, the matrix of a FRP transfers the stresses from the exterior of the FRP component, such as a reinforcing bar, to the individual fibers so the quality of the matrix is extremely important to the function and strength of the FRP. These resins are also used to bond the FRP to a concrete, masonry or timber substrate for externally bonded FRP systems (fib – federation internationale du béton, 2007).

Fig 2.1 Different types of FRP Rods

2.2.1.1 Advantages and Disadvantages of FRP reinforcement

Advantages

- High Strength and Lightweight
- Corrosion Resistant
- Dimensionally Stable
- Low Thermal Conductivity
- Nonconductive
- Electromagnetically Transparent
- Impact Resistant
- Low Lifecycle Costs

Disadvantages

- High Initial Cost (compared to steel reinforcement)
- Susceptibility to Mechanical Damage
- Susceptibility to Fire (without insulation)
- Inability to Bend in the Field
- Longer Load Transfer (Lap) Lengths
- Poor Shear Strength
- Low Strain to Failure (Lack of Ductility)

2.3 Composition of a Structural FRP Reinforcement

A very important issue in the manufacture of composites is the selection of the optimum matrix (Resins) because the physical and thermal properties of the matrix significantly affect the final mechanical properties as well as the manufacturing process. In order to be able to exploit the full strength of the fibers, the matrix should be able to develop higher ultimate strain than the fibers. The matrix not only coats the fibers and protects them from mechanical abrasion and chemical attack, but also transfers stresses between the fibers (fib – federation internationale du béton, 2007).

2.3.1 Typical Strengths

The typical tensile strengths and stress-strain relationship of FRP and steel reinforcements are shown below.

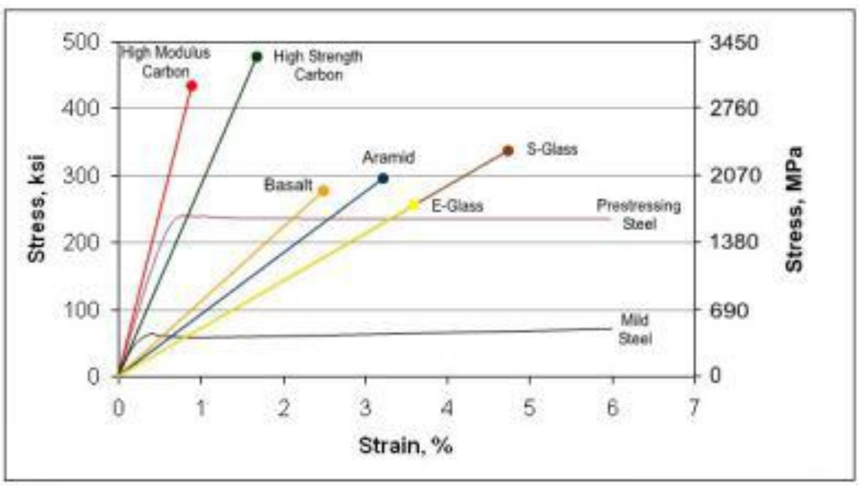


Fig 2.2 Stress-Strain Relationship of FRP and Steel Reinforcements

- E-glass fiber reinforced polymer (GFRP) has the lowest cost of all structural FRPs and is therefore the most utilized.
- Basalt fiber reinforced polymer (BFRP) has a higher cost due to a lack of manufacturer capacity, but with somewhat better strengths than GFRP, resistance to alkalies, and a nearly unlimited resource, its cost is sure to go down.
- Aramid fiber reinforced polymer (AFRP) is not as common a structural reinforcement due to the fibers' low compressive strength perpendicular to the fiber direction and higher

cost. It is this feature, though, that makes aramid fiber the choice of ballistic resistant textiles because the fibers absorb impact very well.

- Carbon fiber reinforced polymer (CFRP) has the highest strength of FRP materials and also the greatest range of strengths. The range is due to the carbon source and manufacturing methods. CFRP is most resistant to creep rupture and fatigue failure than the other FRPs. Its higher cost is offset by its high strength and high resistance to cyclic and fatigue failures.

For this experimental study, E-glass fiber reinforced polymer (GFRP) was used and is briefly stated below.

2.3.2 Glass Fiber

Glass fiber has been the predominant fiber for many structural strengthening and reinforcement applications because of an economical balance of cost and specific strength properties. Two types of glass fibers, E-glass and S-glass, are being made for GFRP (Erki and Rizkalla, 1993). Glass fibers are commercially available in E-Glass formulation (for electrical grade), the most widely used general-purpose form of composite reinforcement, high strength S-2 glass and ECR glass (a modified E-Glass which provides improved acid resistance). Although considerably more expensive than glass, other fibers including carbon and aramid, are used for their strength or modulus properties or in special situations as hybrids with glass. Most GFRP has very low transverse shear strength, which makes it difficult to make prestressing anchorages for GFRP. Surface treatments such as quartz sand to give a rough finish and external fiber winding to produce a ribbed surface have been applied to GFRP rods to improve their bond with concrete. The most extensively used class of fibres in composites are those manufactured from E-glass. E-glass is a low alkali borosilicate glass originally developed for electrical insulation applications (Lukkassen and Meidell, 2007). Glass-fiber reinforced composites (GFRC) are strong, corrosion resistant and lightweight, but not very stiff and cannot be used at high temperatures.

2.3.2.1 Benefits of GFRP

The benefits of GFRP rebar are as follows:

- Corrosion resistance -when bonded in concrete it does not react to salt, chemical products or the alkali in concrete. As GFRP is not manufactured from steel, it does not rust.

- Superior tensile strength -GFRP rebar produced by the pultrusion process offers a tensile strength up to twice that of normal structural steel (based on area).
- Thermal expansion -GFRP rebar offers a level of thermal expansion comparable to that of concrete due to its 80% silica content.
- Electric and magnetic neutrality -as GFRP rebar does not contain any metals, it will not cause interference with strong magnetic fields or when operating sensitive electronic equipment or instruments.
- Thermal insulation -GFRP rebar does not create a thermal bridge within structures.
- Lightweight -GFRP rebar is a quarter the weight of steel rebar of equivalent strength. It offers significant savings in transportation and installation (fib – federation internationale du béton, 2007).

2.4 Application of a Structural FRP Reinforcement

2.4.1 Internal Reinforcement

FRP used as structural reinforcement are used in a wide variety of applications. As internal reinforcement, structural FRPs are produced in the form of bars (rebar), dowels, prestressing, and post-tensioning tendons. Externally bonded or near-surface-mounted FRPs are generally used for structural strengthening and repair of concrete, masonry, timber, and steel structures.

FRP used as internal reinforcement are used in roads, bridges, slopes, tunnels, and marine environments. Internal reinforcement with FRPs has a particular advantage in tunnel diaphragm walls, where steel reinforcement would damage the face of a tunnel boring machine (TBM). Because they are magnetically transparent, FRP reinforcements are used in hospitals where medical scanning equipment such as magnetic resonance imaging is used, in maglev railway ties and structures, and in bases of large electric motors.

Fig 2.3 FRP as Internal Reinforcement

2.4.2 External Reinforcement

Structural strengthening with externally bonded FRP reinforcement, especially with high specific strength carbon FRP, has been accepted by codes for seismic upgrades of structures for a number of years. In flexural strengthening, FRP reinforcement products such as tow sheets, plates, and bars are bonded to the tension side of a concrete, masonry, or timber substrate with a (usually) epoxy resin. In shear strengthening, FRP reinforcements are bonded to the exterior of beams in a vertical U-shape configuration as an external stirrup. Shear strengthening of walls, such as unreinforced masonry walls and under-reinforced concrete walls, can be accomplished by bonding FRPs to one or both sides on the wall in either a vertical, horizontal, or X-pattern (fib– f ederation internationale du béton, 2007).

2.5 FRP Composite manufacturing companies in the World

Below are some of FRP composite manufacturing companies in the world.

- Kodiak Basalt & Fiberglass Rebar (FRP) Manufacturer & Supplier
- Cape Composite (Pty) Ltd- Fiberglass (GRP/FRP) manufactures
- BFG International Pvt-Ltd
- BP Composites (TUFF-Bar)
- Composite Rebar Technologies, Inc.
- Hughes Brothers, Inc. (AslanFRP)
- Marshall Composite Technologies, Inc. (C-Bar)
- Pultrall, Inc. (V-Rod)

- Shijiazhuang-Fayun-Electric-Co-Ltd
- Shijiazhuang-Jiatai-Electric-Power-Fitting-Co-Ltd
- Nanjing-Wish-PhotoElectric-Technology-Development-Co-Ltd
- Hengxing-Composite-Co-Ltd
- Hubei-Yulong-Group-Jinli-New-Materials-Co-Ltd
- Liberty-Pultrusions

2.6 Analysis and Design

Design loads on a reinforced concrete structure are determined using the same methods whether reinforced using steel or using high strength, fiber reinforced polymer (FRP) reinforcing bars. Steel and FRP reinforced concrete members are analyzed using similar methods to meet the following strength and serviceability criteria: Factored moment, factored shear, crack width, and long-term deflection. Additionally, FRP reinforced members are analyzed for creep-rupture stress in FRP bars where steel reinforced members are not (fib – federation internationale du béto n, 2007).

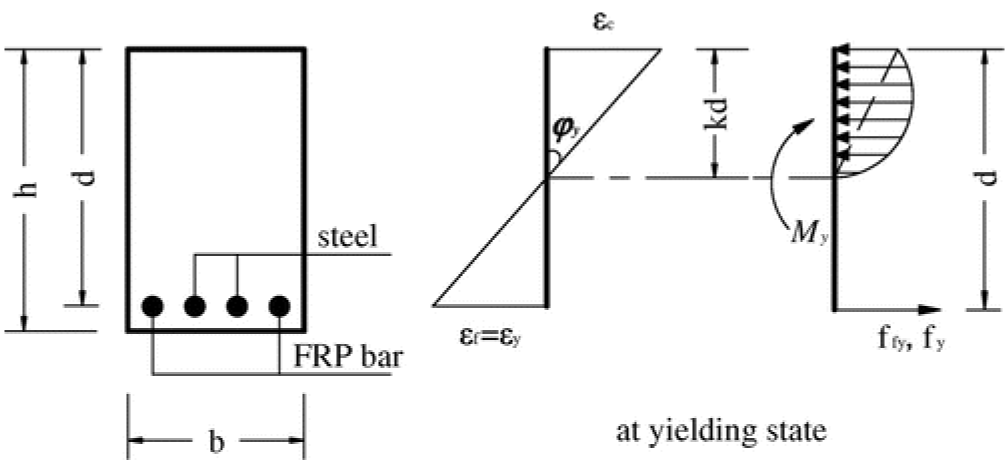


Fig 2.4 Stress-Strain on a Hybrid Steel-FRP rebar reinforced concrete section

In the U.S. and other countries of the world, the American Concrete Institute (ACI) 440.1-06, "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars" is used as the design guidance to calculate the design criteria above for FRP bar reinforced concrete members. In addition, The American Association of State Highway and Transportation Officials (AASHTO) provides guidance in its 2009 "AASHTO LRFD Bridge Design Guide Specifications

for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings, First Edition."
Other standards that provide design guidance are the Canadian Standards Association (CSA) and Federation Internationale du Beton (International Federation for Structural Concrete (fib). For most members, the design of FRP reinforced sections is driven primarily by serviceability requirements: crack width and long-term deflection. An FRP-reinforced concrete member is designed based on its required strength, and then checked for serviceability criteria. This is due to the generally lower modulus of elasticity of FRP bars as compared to steel bars. When these criteria are met, flexural strength (Mn), minimum reinforcement (Af), and creep-rupture stress are generally easily met (ACI 440.1R-15, 2015).

2.7 Near surface mounting technique

Near-surface mounted (NSM) fiber-reinforced polymer (FRP) reinforcement is a latest and most promising strengthening techniques for reinforced concrete (RC) structures. Research on this topic started only a few years ago but has by now attracting attention. Issues raised by the use of NSM FRP reinforcement include the optimization of construction details, models for the bond behavior between NSM FRP and concrete, reliable design methods for flexural and shear strengthening, and the maximization of the advantages of this technique. This paper provides a critical review of existing research in this area, identifies gaps of knowledge, and outlines directions for further research.
More recently, near-surface mounted (NSM) FRP reinforcement has attracted an increasing amount of research as well as practical application. In the NSM method, grooves are first cut into the concrete cover of an RC element and the FRP reinforcement is bonded therein with appropriate groove filler (typically epoxy paste or cement grout). What is herein called "NSM reinforcement" was previously given other names such as "grouted reinforcement", or "embedded reinforcement". Examples of the use of NSM steel rebar in Europe for the strengthening of RC structures date back to the early 1950s. More recent applications of NSM stainless steel bars for the strengthening of masonry buildings and arch bridges have also been documented. The advantages of FRP versus steel as NSM reinforcement are better resistance to corrosion, increased ease and speed of installation due to its lightweight, and a reduced groove size due to the higher tensile strength and better corrosion resistance of FRP (De Lorenzis, 2000). The NSM system has a number of advantages: (a) the amount of site installation work may be

reduced, as surface preparation other than grooving is no longer required (e.g., plaster removal is not necessary; irregularities of the concrete surface can be more easily accommodated; removal of the weak laitance layer on the concrete surface is no longer needed); (b) NSM reinforcement is less prone to debonding from the concrete substrate; (c) NSM bars can be more easily anchored into adjacent members to prevent debonding failures; this feature is particularly attractive in the flexural strengthening of beams and columns (De Lorenzis and Teng, 2006, 2006).

Near surface mounting technique becomes particularly attractive for flexural strengthening in the negative moment regions of slabs and girders, where externally bonded reinforcement could be subjected to severe damage due to mechanical and environmental conditions. The initial research work on NSM technique was reported by Blaschko and Zilch (1999) (Hassan and Rizkalla, 2003) using CFRP strips inserted into grooves cut at the surface of concrete specimens. The specimens were tested in a double shear configuration. Test results showed that strengthening using NSM CFRP strips has a great anchoring capacity compared to externally bonded CFRP strips. De Lorenzis and Nanni (2001) (ACI 440, 2008) investigated the structural performance of simply supported reinforced concrete beams strengthened with NSM glass and carbon FRP rods. Both flexural and shear strengthening were examined. Hassan and Rizkalla (2002) (ACI 440, 2007) investigated the feasibility of using different strengthening techniques as well as different types of FRP for flexural strengthening of large- scale prestressed concrete specimens. The specimens represented typical prestressed concrete slab bridges. Test results showed that the use of NSM FRP bars is feasible and cost effective for strengthening concrete structures and bridges. Hassan and Rizkalla (2003) investigated the bond performance of concrete structures strengthened with NSM CFRP strips. A closed-form analytical solution was proposed to predict the interfacial shear stresses and the minimum anchorage length needed to effectively use NSM FRP strips. The model was validated by comparing the predicted values with test results as well as non-linear finite element modeling. DeLorenzis and Nanni (2002) (De Lorenzis and Nanni, 2002) examined the bond between NSM FRP bars and concrete by testing 22 unreinforced concrete beams having a span of 1067 mm and strengthened with NSM FRP bars. The influence of different parameters including the bonded length, diameter of the bars and type of FRP materials were investigated. The effect of the internal steel reinforcement configuration on the bond behavior was not demonstrated since the tested specimens were unreinforced. Moreover, the influence of the size effect using small-size specimens on the bond behavior might be significant and was not included in their proposed model. Blaschko (ACI 440, 2004) introduced an analytical model for the bond of NSM CFRP strips. The model showed that the deformations in the concrete have a strong influence on the distribution of the bond stresses and therefore on the bond capacity. And further experimental works done and their results using the NSM FRP reinforcement on concrete structures are stated below.

2.8 Previously done Field/Site works on FRP composites

In Europe, 1948, an RC Bridge in Sweden experienced an excessive settlement of the negative moment reinforcement during construction, so that the negative moment capacity needed to be increased. This was accomplished by grooving the surface, filling the grooves with cement mortar and embedding steel rebar in them. All the technological and design problems and considerations are reported by Asplund (Asplund, 1949). Nowadays, FRP rods can be used in place of steel and epoxy paste can replace cement mortar. The advantage is primarily the resistance of FRP to corrosion, a property that is particularly important in this case due to the position of the rods very close to the surface (De Lorenzis et al., 2000). Very limited literature is available to date on the use of NSM FRP rods for structural strengthening. Laboratory studies are reported in Warren (1998), Yan et al. (1999), Crasto et al. (1999), and De Lorenzis (2000).

A strengthening project was carried out to upgrade the structural floor of Myriad Convention Center, Oklahoma City, OK (USA) in 1997-1998. A combination of externally bonded steel plates, Carbon FRP (CFRP) sheets and NSM CFRP rods was adopted. NSM rods were used in this case for shear strengthening of one of the RC joists. Vertical grooves 1/2-in. wide and 3/4-in. deep with a total length of 20 in. were saw-cut along the side surfaces of the joist at such positions that existing stirrups were avoided as shown in Fig 2.5. CFRP No. 3 rods were then inserted in the epoxy filled grooves (Hogue, 1999).

Fig 2.5 Vertical Grooves for shear strengthening with NSM FRP Rods

NSM CFRP rods were used for strengthening of two RC circular structures in the United States in 1998. Longitudinal and transverse grooves 1/2-in. wide and 1/2-in. deep were cut on the surface of the structures and CFRP sandblasted rods with a nominal diameter of 5/16 in. were embedded in the epoxy-filled grooves (De Lorenzis et al., 2000) shown in Fig 2.6.

Fig 2.6 Grooves Prepared and filled with Epoxy Paste on the surface of the structure

Pier 12 at the Naval Station San Diego, CA (USA) was strengthened in November 1998 to meet demand of higher vertical loads. NSM CFRP rods were used to increase the capacity of the deck slab in the negative moment regions. Slots were saw-cut in the deck in the range of 7/8-in. deep and 5/8-in. to 3/4-in. wide. CFRP pultruded No. 3 rods were placed in sequence into the epoxy-filled slots and pressed to the bottom (Fig 2.7). After the epoxy was cured, the surface was abrasive blasted and a UV protective layer was added to the top of the slot. After completion of the upgrade, some spans of the deck were tested. Strain gages were attached to the CFRP rods in order to monitor the performance of the strengthening system, which proved to be satisfactory (Warren, 1998).

Fig 2.7 Embedding CFRP Rods in the Top Surface of the Deck

Bridge J-857, located on Route 72 in Phelps County, MO (USA), was strengthened in August of 1998 while in service. One of the three solid RC decks was strengthened using NSM FRP rods. The NSM reinforcement consisted of CFRP sandblasted rods with 7/16-in diameter. Strengthening to approximately 30% of the nominal moment capacity was desirable in order to upgrade the bridge decks for HS20-modified truck loading. The design called for 20 NSM CFRP rods spaced at 15 in. on-center. The rods were embedded in 20-ft long, 3/4-in. deep, and 9/16-in. wide grooves cut onto the soffit of the bridge deck parallel to its longitudinal axis, as shown in Fig 2.8. Strain gages and fiber optics sensors were applied to concrete, steel and FRP reinforcement to monitor strain during testing. Each of the three decks was tested to failure by applying quasi-static load cycles. For the deck with NSM rods, failure was initiated by the rupture of some CFRP rods at the location of the widest crack. This deck exhibited the highest failure load, corresponding to an increase in moment capacity of 27% over the un-strengthened deck. Two columns were also strengthened with NSM CFRP rods to increase their flexural capacity (Fig 2.9). The rods were mounted on two opposite faces of the columns and anchored 15 in. into the footings (Alkhrdaji, 1999).

Fig 2.8 Installation of NSM CFRP Rods in the Bridge Deck

Fig 2.9 Columns Strengthened with NSM Rods

A strengthening and load-testing program at the decommissioned Malcolm Bliss Hospital in St. Louis, MO (USA) was conducted in 1999. In the building, a five-story RC-frame addition built in 1964, static load tests up to failure were carried out in order to validate strengthening of masonry walls and RC joists using externally bonded FRP laminates and NSM FRP rods. The program on masonry walls strengthened with FRP composites included testing of unreinforced masonry walls subjected to out-of-plane loading and reinforced masonry walls under in-plane loading. Fig 2.10 shows the installation of NSM FRP rods on a masonry wall to be strengthened for out-of-plane (Tumialan, 1999).

Fig 2.10 Installation of NSM FRP Rods on Masonry Walls

2.9 Critical Observation from the Literature Review

From the reviews of literature above, the application of the NSM FRP in the different tested showed an increase in efficiency and strength of the concrete structures. In the review, it is clear that, only some of these models predicted the full behavior of RC beams which will put a demand for more tests and experiments on these techniques to understand the full behaviors of the concrete structures. Another critic is most of the literatures done on FRP composite didn't show the procedures they used for the analysis and design FRP reinforced members which requires for more elaborated procedures. The NSM technique used in most of the reviews didn't state the effect of debonding of the FRP rods and its solutions which is critical for the performance of the strengthened RC members.

Chapter 3

3. Materials and Methodology

This experimental study was conducted at Addis Ababa institute of technology (AAIT) material laboratory. For this experimental study, a total of ten small scaled reinforced beams were investigated using standard beams of size 150x150x750 mm rectangular cross-section. For the first trial tests, Glass FRP rods of #3 (Ø10mm) and #4 (Ø13mm) were embedded in the grooves cut into the bottom concrete surface and then filled with viscous epoxy-resin paste. An internal steel flexural reinforcement on the tension side consisted of three deformed 10-mm steel rebar, two deformed 10 mm steel rebar on the compression side and diameter 8-mm stirrups. A control beam Bo-1 and Co-1 were used for comparison with the retrofitted and strengthened beams for the first and second trial tests respectively. In the first trial, specimen beams, B-1 and B-2, were strengthened with two 10mm GFRP rod and local available epoxy resin was used as a filler material between the concrete and FRP rod shown in Fig 3.1. Specimen beams B-3 and B-4 were strengthened with two 13 mm GFRP rod. The details of the beams cross-section are illustrated in Fig 3.2. Specimen beam B-5, was strengthened with one 10 mm GFRP rod shown in Fig 3.3. Epoxy resin is also used as a filler material in the prepared groove between the FRP and the concrete. For the second trial tests, only Glass FRP rods of #3 (Ø10mm) was inserted into the bottom concrete surface and then filled with cement mortar. In the second trial tests, specimen beam, C-1 was strengthened with one 10 mm inserted at the bottom surface of the beam as shown in Fig 3.4.

Groove preparation of specimen beams C-2 and C-3 have a different configuration than near surface mounting of the FRP material and were added to this experiment to recommend further repairing methods. These beams were strengthened with one 10 mm inserted in between the bottom reinforcement of the beam as shown in Fig. 3.5 and cement mortar is also used as a filler material. The concrete strength and the GFRP rods used for this experiment were the same for all specimens.

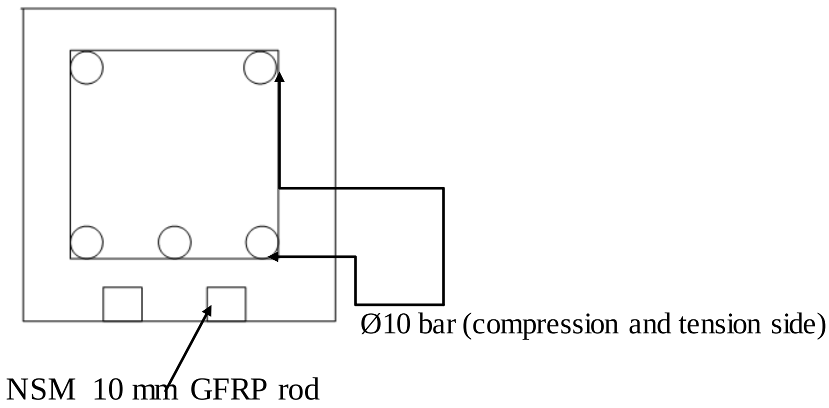


Fig 3.1 Beam Cross-section for B-1 and B-2

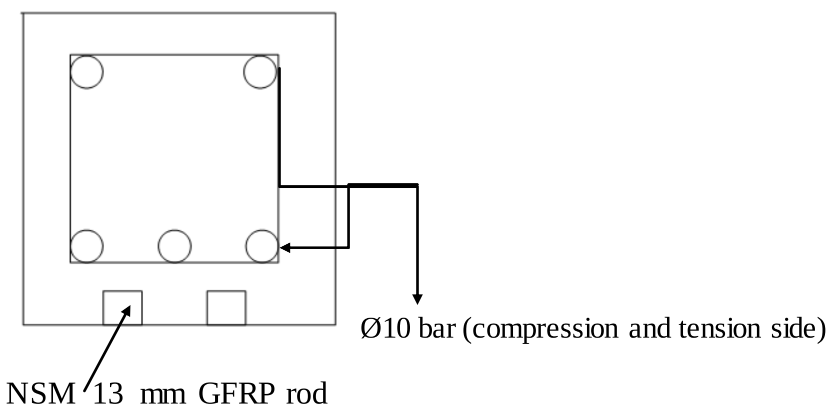


Fig 3.2 Beam Cross-section for B-3 and B-4

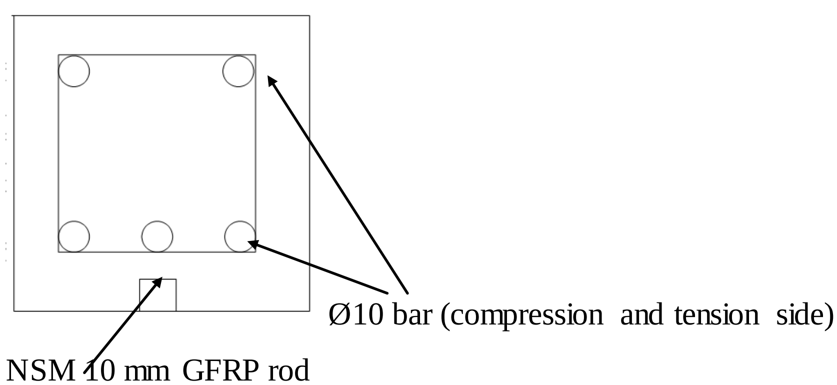


Fig 3.3 Beam Cross-section for B-5

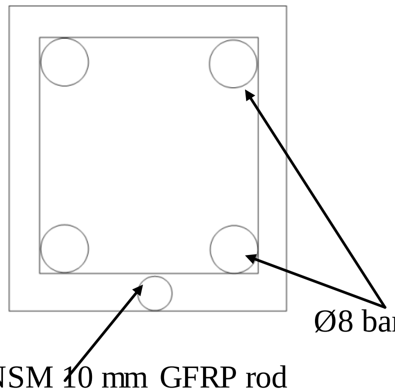


Fig 3.4 Beam Cross-section for C-1

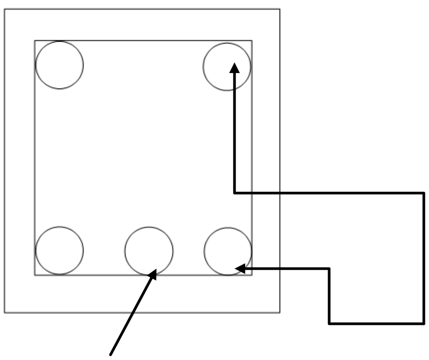


Fig 3.5 Beam Cross-section for C-2 and C-3

The NSM FRP rods were prolonged until the beam ends, to simulate a real situation with the rods into the adjacent structural members (De Lorenzis, 2002).

3.1 Material property

3.1.1. Concrete

After 24 hours of the casting process, the concrete samples were removed from the molds and then immersed in a water tank for seven days. All specimens were then removed from water curing tanks and stored in the laboratory air at 25 C^0 until testing started after the age of 28 days. The average concrete strength from the mix ratio was 33 MPa and three 150mm cube and three 150 mm dia. by 300 mm cylinder concrete specimens were tested for compression strength tests.

Fig.3.6 curing of the concrete beam specimens

3.1.2 Reinforcing steel bar

The longitudinal steel reinforcing bars used for the first trial beams were deformed, high-yield strength of size 10 mm diameter and 8 mm dia. stirrups with spacing 50mm. For the second trial beams, 8mm longitudinal steel reinforcing bars with 8 mm dia. stirrups of spacing 30mm were used. Three coupons from each type of steel bar were tested. Yield strength of steel reinforcements is determined under uni-axial tension test. The averaged ultimate and yield tensile strength of the specimens for 8 mm steel bar is 559 Mpa and 430.89 Mpa respectively. And for that of 10mm are 520.09 Mpa and 369.04 Mpa respectively.

3.1.3 FRP rod

Wrapped surface Glass FRP rods of diam.10mm (#3) and 13mm (#4) were used for flexural strengthening of the beams. The nominal area for #3 and #4 Glass FRP rods are 86 mm^2 and 139 mm^2 respectively. According to the manufacturer data, the effective yield strength and Ultimate tensile strength for #3 is 800 MPa and 1000 MPa respectively. And for that of #4 Glass FRP is 965MPa and 772MPa respectively.

Fig.3.7 Vinyl-ester resins + Wrapped Surface GFRP rod

3.1.4 Epoxy Resin

The success of the strengthening technique primarily depends on the performance of the epoxy resin used for bonding of FRP to concrete surface (Naveen, 2013). Numerous types of epoxy resins with wide range of mechanical properties are commercially available in the market. For this experimental thesis, a commercial available epoxy resin was used. The epoxy resin is generally available in two parts, a resin and a hardener. According to manufacturer data, its Com pressive Strength (ASTM C 579) 72 MPa, flexural Strength (ASTM C 580) 32 MPa, tensile Str ength (ASTM C 307) 18 MPa.

3.2 Mix Design Values and Procedures

The specified compressive strength of concrete is 33MPa at 28 days. Ordinary Portland cement was used of 32.5grade. According to ACI 211.1-81(Revised 1985), Table A1.5.3.3, the mixing water content calculated is 184 kg/m3.

Table 1 Mix Proportion

Water	Cement	Fine Aggregates	Coarse Aggregates
184	408.89 kg	828.57 kg	1054.94 kg
0.45	1	2.02	2.58

Table 2 Concrete mix design quantities:

Grade of concrete: C-30	Coarse aggregate(20mm) : 2.51
Type of exposure: Normal	Fine Aggregate: 3.22
Sp. Gravity of cement: 3.15	Maximum Water Cement Ratio: 0.45

Table 3 Quantity of Materials for casting beams considering 20% wastages

Materials	One mould (in kg)	Five moulds (in kg)
Cement	8.28	41.4
Fine aggregate	17.441	87.207
Coarse aggregate	20.069	100.343
Water	3.908	19.539
TOTAL	49.698	248.489

3.3 Flexural Testing procedures

3.3.1 Tests and setups

The RC beams were loaded under center-point bending test with 590 mm distance between supports. This test method is used to determine the flexural strength of specimens prepared and cured in accordance with test methods of ASTM C293, "Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Center-Point Loading" (ASTM C293). Load was applied by a means of a hydraulic jack connected to an electric pump and recorded with a load cell. Each beam was instrumented with two LVDT placed at mid-span on both sides of the concrete beam. Stain gauges were instrumented at the mid-span on the bottom face on the steel rebar and FRP rods. The loading arrangement was the same for all the beams. The load at which the first visible crack is developed was recorded as a cracking load. The loading was continued until failure.

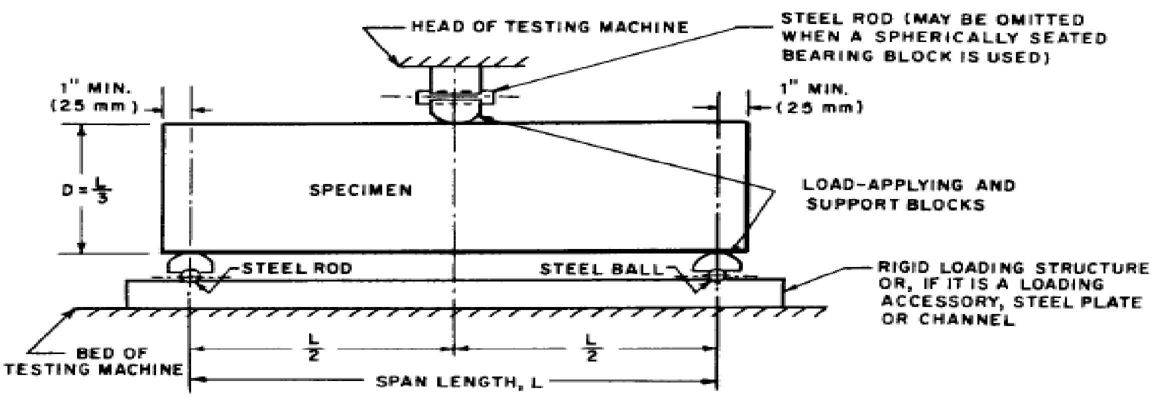


Fig.3.8 Diagrammatic View of a Suitable Apparatus for Flexure Test of RC beam specimen by Center-Point Loading Method

3.3.2 Preparation and casting of GFRP onto the bottom surface

The strengthening activities were executed with the beams in the hardened state. For the first trial test beams, installation of the NSM FRP rods began by making a series of grooves with specified and marked dimensions cut into the concrete cover in the longitudinal direction at the tension side of the beam specimens. These grooves were chiseled according to De Lorenzis (De Lorenzis, 2002). For round bars, based on results of bond tests with square grooves ($b_g = h_g$) and defining $k = b_g / d_b$, proposed a minimum value of 1.5 for k for smooth or lightly sand-blasted bars and a minimum value of 2.0 for k for deformed bars. Taking k=1.5 for wrapped GFRP bar with d_b= 13mm used for this study, the groove cross-section would be b_g = 20mm and h_g = 20mm (De Lorenzis et al., 2006).

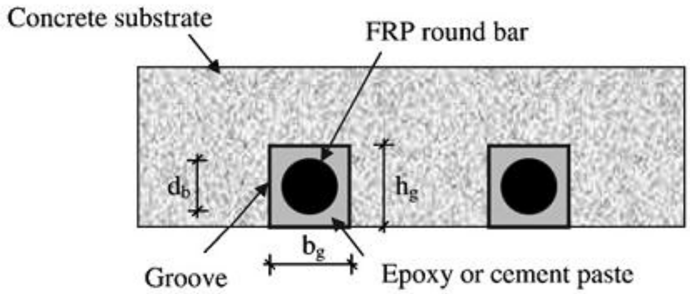


Fig 3.9 NSM system and nomenclature

A special concrete saw with a diamond blade was used to cut the grooves with the dimensions as shown in Fig. 3.10. After the sides of grooves have been cut, the unnecessary sides of the groove are chiseled off. The concrete surface is made rough using a coarse sand paper texture to remove all dirt and debris. The adhesive is prepared and applied into the groove before inserting the FRP reinforcing bars. The epoxy resin was mixed in accordance with manufacturer's instructions. The mixing is carried out in a plastic container. After uniformly mixing, the epoxy resin is applied to the grooved concrete surface. Then the GFRP rod is placed on top of an epoxy resin coating. During hardening of the epoxy, a constant uniform pressure is applied in order to extrude the excess epoxy resin and to ensure good contact between the epoxy, the concrete and the GRFP rod as shown in Fig. 3.11. This operation is carried out at room temperature. Testing of the beams continued after 24 hour upon hardening of the epoxy resin within the groove.

Fig.3.10 Groove preparation saw cut and chiseled.

Fig.3.11 FRP rod inserted into epoxy resin at the bottom surface of the beam.

For the second trial tests, pipes were inserted at the bottom surface before casting the beams and pulled out which will leave space for the insertion of FRP materials as shown in Fig.3.12. These pipes were used instead to compare and investigate with trial one method of chiseling and to show the effects caused by it like minor cracks and concrete cover wearing off, which affects the strength of the concrete. For beam C-1, the pipes were inserted below the stirrup that is near the surface of the bottom surface. For beams C-2 and C-3, the pipes were inserted above the stirrup that is between the bottom tension reinforcement. This was done to examine and compare the results with the first trial beams and having the idea of leaving space for further repairing and rehabilitation mechanisms, by using pipes in the structural members which are prone to damage.

Fig.3.12 Pipes casted in the bottom surface of the beam.

3.3.3 Loading until failure

Load was continuously applied till the ultimate failure of the beams. The gradual increase in load, the mid-span deflection from the LVDT and the deformation in the strain gauge reading are taken throughout the test. The data furnished in this chapter have been interpreted and discussed in the next chapter to obtain a conclusion.

Fig.3.13 Test setup of specimen

Chapter 4

4. Results and Discussion

The experimental results for the tested concrete beams would be discussed in this chapter. The different behaviors and characters of the tested beams throughout the experiment were presented here. The crack pattern and the failure modes for each beam would also be described.

4.1 Test Result

The concrete beam specimens were loaded until failure. All beams were strengthened with NSM GFRP at hardened state. These beams were loaded with the same type of load arrangement. Summary of test results of trial 1 and trial 2 specimens are presented in Table 4 and Table 5 respectively.

Table 4.1 Trial 1 specimens Summary and Results

Beam	**Flex. Reinf. (Tension)**	**FRP Reinf.**	**Ultimate Load (kN)**	**Failure Mode**	**% Increase over Control**
B0-1	3Ø 10	-	82.1	Flexure	-
B-1	3Ø 10	2 Ø 10	97.1	Flexure, DB	18.27
B-2	3Ø 10	2 Ø 10	93.8	Flexure, DB	14.25
B-3	3Ø 10	2 Ø 13	103.1	Shear before SY	25.58
B-4	3Ø 10	2 Ø 13	98.3	Shear before SY	19.73
B-5	3Ø 10	1 Ø 10	90.86	Flexure, DB	10.67

DB = Debonding of the GFRP; SY= Steel Yielding

Table 4.2 Trial 2 specimens Summary and Results

Beam	Flex. Reinf. (Tension)	FRP Reinf.	Ultimate Load (kN)	Failure Mode	% Increase over Control
Co-1	2Ø 8	-	45.4	Flexure	-
C-1	2Ø 8	1 Ø 10	56.7	Flexure	24.89
C-2	2Ø 8	1 Ø 10	59.3	Flexure	30.62
C-3	2Ø 8	1 Ø 10	61.6	Flexure	35.68

4.2 Discussion

4.2.1 Analysis of the failure modes

The Fig. 4.1 to 4.7 shows the observed failure modes. For beams Bo-1, B-1, B-2 and B-5, the primary mode of failure was flexure with steel yielding. The flexural strength of the beam is reached with yielding of the tensile steel reinforcement, followed by loss of bond (debonding) between the GFRP rod and the concrete surface as shown in Fig 4.3. Second observed mode of failure was shear failure as in the case of B-3 and B-4 beams. For this beams, the addition of GFRP rod in the tension zone increased the reinforcement ratio which was high and led to failure of the RC element caused by compressive crushing of the concrete before the tensile reinforcement yielded as shown in Fig 4.2. For the second trial concrete beams, Co-1 to C-3, mode of failure was a flexure failure as shown in Fig 4.4 to Fig.4.5.

Fig.4.1 Failure Photo of Beam Bo-1

Fig.4.2 Failure Photo of Beam B-3

Fig.4.3 Debonding of GFRP rod shown on Photo of Beam B-5

Fig.4.4 Failure Photo of Beam Co-1

Fig.4.5 Failure Photo of Beam C-1

4.2.2 Analysis of RC beams with GFRP rods inserted into grooves

In the first trial tests, FRP was inserted into the grooves made near the surface of the tension side of the concrete and epoxy was used as a filler material. From the results shown above, debonding of the GFRP rod occurred after steel yielding. Due to this debonding effect, the beams capacity wasn't increased by much above the design load. As for the second trial beam, the GFRP was inserted into the whole made with a pipe casting. The debonding effect of the GFRP rod from the concrete tension side was avoided but because the filler material used was concrete mortar, the ultimate capacity wasn't much greater than the design load. However, it appears that bond is of critical importance for the effectiveness of this technique. These failures can be avoided by increasing the groove width, increasing the epoxy cover layer and providing anchorage system as shown in Fig.4.6 below. For C-2 and C-3, the same effect of debonding was avoided and showed as enhancement in ultimate load carrying capacity. A more advanced chemical bonding like that of the epoxy adhesive can be used for trial tests to give a better result.

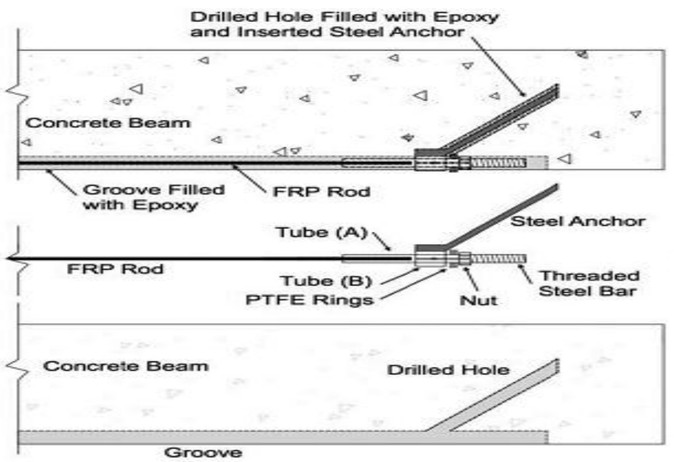


Fig.4.6 Schematic diagram of the setup and prestressing system (fib – federation internationale d u béton, 2007)

4.2.3 Analysis of Load- Deflection Curve

The flexural stiffness of strengthened reinforced concrete beams is compared with that of the corresponding control beams using the load versus deflection curves. The load-deflection behaviors of the beams are shown in the figures Fig. 4.7 and Fig.4.8.

Beam Bo-1 and Co-1, the control beams, reached failure after the yielding of the steel. After yielding, the control beams had a flat load-deflection behavior, whereas in the strengthened beams yielding of the steel rebar led to a reduction in slope, but the GFRP rod allowed the beams to withstand additional load. Due to the NSM FRP strengthening, a moderate increase in stiffness was achieved on the region between cracking of the concrete and yielding of the steel longitudinal as shown in Fig. 4.7 and Fig.4.8. In terms of strength and stiffness, the strengthened beams with NSM bonded FRP system performed significantly better than the control (un-strengthened) beam. The strength of RC beams reinforced with NSM FRP system is influenced by the concrete strength of the beams, the amount of NSM FRP rods used and the adhesion used between the concrete and the FRP.

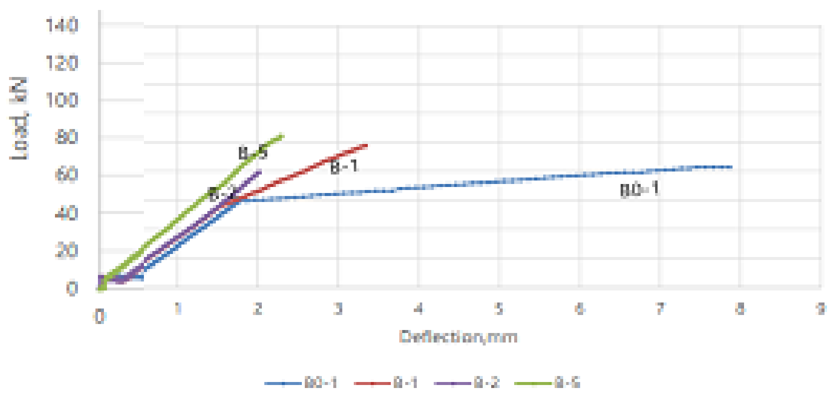


Fig.4.7 Load-Deflection Behavior of First trial tested RC Beams

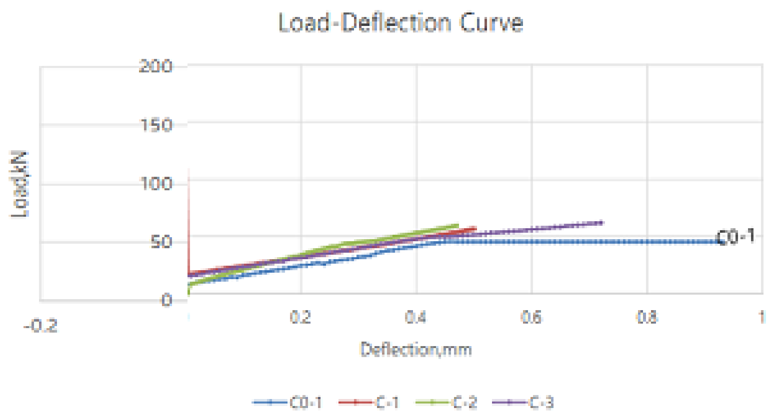


Fig.4.8 Load-Deflection Behavior of Second trial tested RC Beams

4.2.3 Analysis of Load-Strain Curve

The load-rebar strain responses are shown in Fig. 4.9 and Fig. 4.10. These strain data were recorded using the electrical resistance strain gauges and these data terminated at the points where the gauges lost their effectiveness. The attached GFRP rods worked as a tensile reinforcement and shared the applied load with the internal steel reinforcement. The load at which the FRP yielded was higher for the strengthened beam, proposing that internal resistance forces were shared between the steel and FRP. Most of the increase in load-carrying capacity was obtained after the rebar yielding point, indicating that GFRP rod works efficiently in tension after yielding of the rebar.

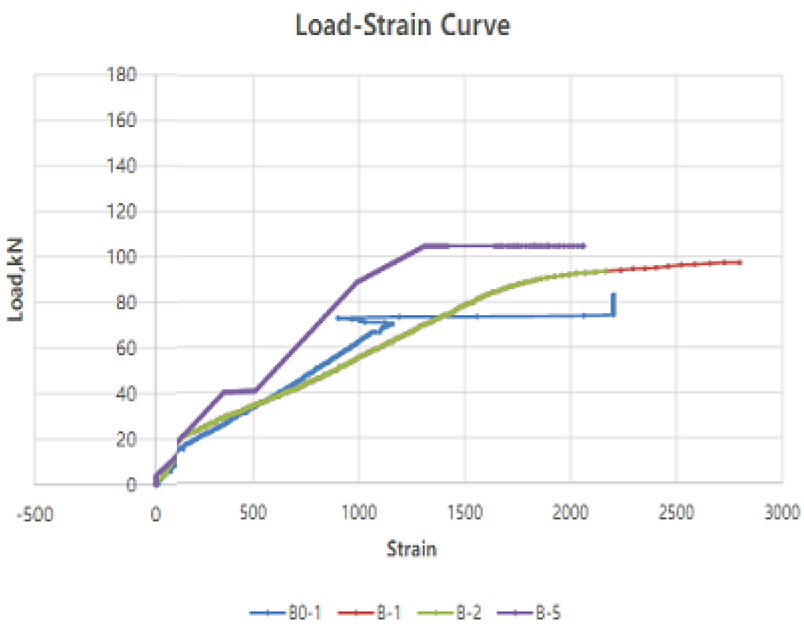


Fig.4.9 Load-Strain Response at the Mid-Span of first trial Beams

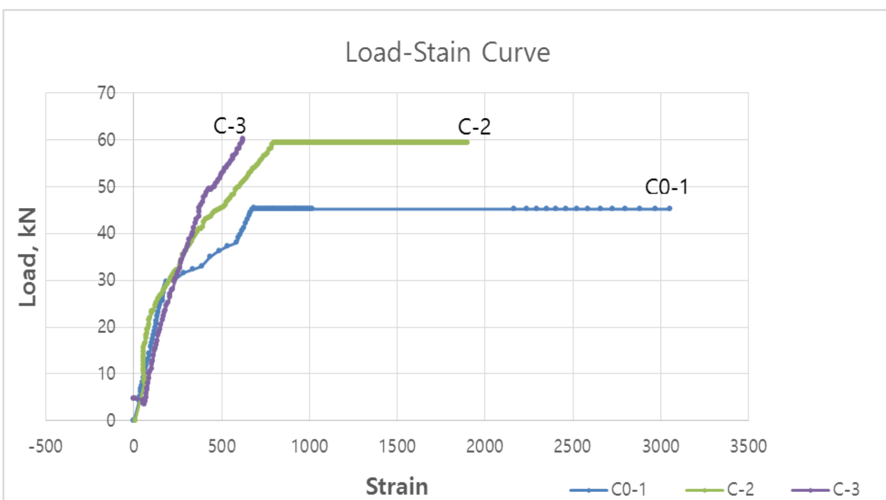


Fig.4.10 Load-Strain Response at the Mid-Span of second trial Beams

Chapter 5

5. Conclusion and Recommendations

5.1 Conclusion

Ten small scaled reinforced concrete beams, two control and seven strengthened beams, were tested, in which NSM GFRP rods were used for flexural strengthening. The test results confirm that the tested beams, an increase in the ultimate load carrying capacity of the strengthened beams ranged from 14.25% to 25.58% increase over the control beam for the first trial beams and 24.89% to 35.68% increase over the control beam for the second trial beams was achieved. The strengthened beams showed a result of an increase in strength and stiffness and a decrease in deflection as compared to the control beam. These results showed that NSM GFRP rods can be used to significantly increase the flexural load carrying capacity of RC elements which implies that this technique can be applicable for repairing and strengthening of damaged RC beam members.

5.2 Recommendation

- Full scale beam specimens to check the actual behavior for the NSM FRP retrofitted or repaired RC member properties.
- Cost analysis should be done on the different methods of maintenance of structures.
- Usage of Advanced chemical bonding epoxy adhesive filler material can give better results.
- Further tests on Bond and Beam pullout tests should be done to minimize debonding effects.
- Further study on anchorage systems to minimize debonding effects.
- Proposing the idea of leaving space within the structural member for further maintenance and repairing.

References

ACI 440, 2004. “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures”, ACI 440.3R-04, American Concrete Institute.

ACI 440, 2007. “Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures”, ACI 440R-07, American Concrete Institute.

ACI 440, 2008. “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures”, ACI440.2R-08 (DRAFT), American Concrete Institute.

ACI 440.1R-15 “Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars,” ACI Committee 440, American Concrete Institute, Farmington Hills, Mich., (2015).

Alkhrdaji, T., Nanni, A., Chen, G., and Barker, M., (1999), “Upgrading the Transportation Infrastructure: Solid RC Decks Strengthened with FRP,” Concrete International, American Concrete Institute, **21**:37-41.

Asplund, S.O. (1949), "Strengthening Bridge Slabs with Grouted Reinforcement", Journal of the American Concrete Institute, **20**: 397- 406.

ASTM C293. “Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Center-Point Loading" , Annual book of ASTM standards, vol 04.02, ASTM international, West Conshohocken, PA, United States.

Dag Lukkassen and Annette Meidell "Advanced Materials and Structures and their Fabrication Processes" Narrik University College, Hin, 2007.

De Lorenzis L., Francesco M., Antonio La,T. (2002) , “Passive and Active NSM FRP rods for Flexural strengthening of RC beams”, University of Lecce, Italy.

De Lorenzis, (2002), “Strengthening of RC structures with near surface mounted FRP rods”, PHD thesis, Department of Innovation Engineering, university of Lecce, Italy.

De Lorenzis, and A. Nanni, (2002), “Bond Between Near Surface Mounted FRP Rods and Concrete in Structural Strengthening”, ACI Structures Journal, **99**:123-133.

De Lorenzis, L. (2000). “Strengthening of RC Structures with Near-Surface Mounted FRP Rods”, MSc Thesis, Department of Civil Engineering, The University of Missouri – Rolla, Rolla, MO, 175 pp.

De Lorenzis, L. and Teng, J.G., (2006), “Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures”, Composites Part B: Engineering, **38**: 119-143.

De Lorenzis, L., Nanni, A., and La Tegola, A., (2000), "Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods”, International Meeting on Composite Materials, PLAST, Milan, Italy, May 9-11.

De Lorenzis, L., Nanni, A., and La Tegola, A., (2000), "Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods", bibl. International Meeting on Composite Materials, PLAST 2000, Milan, Italy.

Di Ludovico M., Prota, A., Manfredi, G., and Cosenza, E. (2010) “FRP strengthening of full-scale PC girders”, Journal of Composites for Construction, **14**:510–520.

Erki, M. and Rizkalla, S.H., (1993), "FRP Reinforcement for Concrete Structures," AC1 Concrete International Journal, **15**: 48-53.

Hacan Nordin- Thesis, (2003), “Fiber Reinforced Polymers in Civil Engineering Flexural Strengthening of Concrete Structures with Pre-stressed Near Mounted CFRP rods”.

Hassan T. and Rizkalla S., (2003), “Investigation of Bond in Concrete Structures Strengthened with Near Surface Mounted Carbon Fiber Reinforced Polymer Strips”, Journal of composite for construction.**7**:248.

Hogue, T., Cornforth, R.C., and Nanni, A. (1999), “Myriad Convention Center Floor System Reinforcement”, Proceedings of the FRPRCS-4, C.W. Dolan, S. Rizkalla and A. Nanni, Editors, ACI, Baltimore, MD, pp. 1145-1161.

Ibrahim, A.M., Mahmood, M.S. (2009), Finite element modeling of reinforced concrete beams strengthened with FRP laminates, European Journal of Scientific Research. **30**:526–541.

International Federation for Structural Concrete (fib – federation internationale du béton) Task Group 9.3. “FRP reinforcement in RC structures”, September 2007, Vol. 4, Issue 6, June 2015.

Ministry of Work & Urban Development, Ethiopian Building Code Standard Part 2: Structural Use of Concrete, EBCS part 2, 1995.

Naveen sure, (2013), “Experimental and Analytical study on torsional behavior of RC Flanged beams strengthened with Glass FRP”.

Taerwe, L., (1995) ed. Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Second International RILEM Symposium (FRPRCS-2), E&FN Spon, London, UK ISBN 0 419205403.

Tong L., Mouritz A.P. and Bannister M.K., (2002), “3D Fiber Reinforced Polymer Composites”, Elsevier Science Ltd, Oxford, UK, **8**:241.

Tumialan, G., Tinazzi, D., Myers, J., and Nanni, A. (1999), "Field Evaluation of Masonry Walls Strengthened With FRP Composites at the Malcolm Bliss Hospital", Report CIES 99-8, University of Missouri-Rolla, Rolla, MO.

Warren, G.E. (1998), Waterfront Repair and Upgrade, Advanced Technology Demonstration Site No. 2: Pier 12, NAVSTA San Diego, Site Specific Report SSR-2419-SHR, Naval Facilities Engineering Service Center, Port Hueneme, CA.

Yan, X., Miller, B., Nanni, A., and Bakis, C.E. (1999), "Characterization of CFRP Bars Used as Near-Surface Mounted Reinforcement", Proceedings 8th International Structural Faults and Repair Conference, M.C. Forde, Ed., Engineering Technics Press, Edinburgh, Scotland.

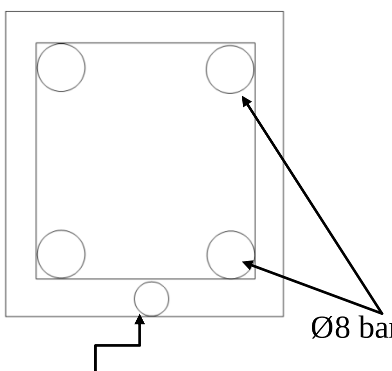
Appendix

Flexural Design example of NSM_GFRP Rods based on Simplified formula from "**Study on the Flexural Capacity of Concrete Beam Hybrid Reinforced with FRP Bars and Steel Bars**", the 5th International Conference on FRP Composites in Civil Engineering September 27-29, 2010 Beijing, China.

Concrete properties: $f_c = f_{ck}$ = 30/1.25= 24 Mpa (normal weight concrete)

Steel reinforcement properties: f_y = 400 Mpa,

Glass fiber rods properties: E_f =50 Gpa (Manufacturer Data)



b = 150 mm

d= 150-Ø8-Ø8/2-25=113 mm

L = 75-2*8= 59 mm

ρ_s = A_s/(bd)= (2*π*8^2/4)/ (150*113) = 0.006

ρ_f = A_f/(bd) = (1*π*10^2/4)/ (150*113) = 0.0046

$$A = \frac{f_y \rho_s}{f_c}$$

A = (400*0.006)/24 = 0.1

$$B = \frac{0.0033 E_f \rho_f}{f_c}$$

B= (0.0033*50*0.0046)/24

$\boxed{B= 0.035}$

$$\xi = \frac{A - B + \sqrt{(A-B)^2 + 3.2B}}{2}$$

$$= \frac{0.1-0.035 + \sqrt{((0.1-0.035)^2 + 3.2*0.035)}}{2}$$

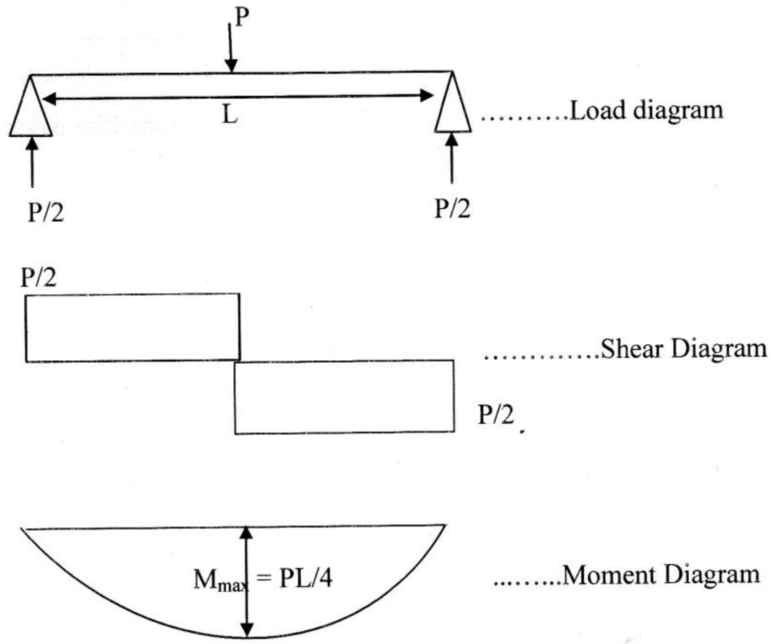
$$= \frac{0.1-0.035+0.341}{2}$$

ξ = 0.203

$$M_u = f_c b h_0^2 \xi (1 - \xi / 2)$$

= 24*150*113^2*0.203 (1-0.203/2)

M_u = 8.38 KN-m……………………………………………………..Moment Capacity



$M_{max} = M_u = PL/4$

$$P = \frac{4 * M_u}{L}$$

$$\boxed{P = \frac{4 * 8.38}{0.59} = 56.81 \text{ KN}}$$

V_{RD} = Shear resistance of the member

$= 0.25 f_{cd}\, b_w\, d$

$= 0.25*13.6*150*113$

$$\boxed{V_{RD} = 57.63 \text{ KN} > V_{Sd}}$$

V_c = Shear resistance of the concrete

$= 0.25 * f_{ctd} * k_1 * k_2 * b_w * d$

$= 0.25(f_{ctk} / \gamma_c) * k_1 * k_2 * b_w * d$

$k_1 = 1+50\rho \leq 2$	$k_2 = 1.6 - d$	$f_{ctk} = f_{ctk} / \gamma_c$
$= 1+50(0.006)$	$= 1.6-0.113$	$= 1.7/1.5$
$= 1.297 \leq 2$	$= 1.487$	$= 1.13$ Mpa

45

$V_c = 0.25*1.13*1.297*1.487*150*113$

$\boxed{V_c = 9.238\ KN}$

V_s = Shear resistance of a member with shear reinforcement

$$= \frac{A_V * d * f_{yd}}{s}$$

$Av = 2(2*\pi*\ 8^2/4)$
$= 100.53\ mm^2$

s = 30 mm (assumed)

$$V_s = \frac{100.53*113*348}{30}$$

$\boxed{V_s = 131.8\ KN}$

$V_c + V_s = 131.8+9.238$
$= 141\ KN$

$V_c + V_s > V_{sd}$

141 KN > 56.81 KN ……………Ok!

Use ø 8/ 30mm stirrups.